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Advances in Wearable Multifunctional Devices Based on Human-Body Energy Harvesting

Huaqing Chu, Jiangtao Xue, Dan Luo, Hui Zheng, and Zhou Li**

Wearable electronics with multi-functionalities are widely utilized in various domains, including everyday living, healthcare, military training, and sports. Advances in flexible electronic technology, new materials, artificial intelligence technology, and sensor technology have accelerated the rapid development of smart wearable devices toward multifunctional and highly integrated trends. The energy supply technology based on the human-body energy harvesting method endows wearable, multifunctional electronic devices with sustainable, renewable, and self-powered characteristics, which proposes a solution strategy for the function expansion and energy supply of wearable devices. Herein, this paper discusses recent research on various methods of harvesting human body energy and wearing parts respectively, focusing on the new materials, structures, and processes involved in the representative studies, as well as the impact on energy harvesting and output, and functional applications. Furthermore, the challenges and obstacles faced in the creation of wearable multifunctional devices based on human self-sufficiency and propose solution strategies to propel them in order to advance the creation of the next wave of intelligent wearable technology are also discussed.

1. Introduction

Smart wearable technology has been updated and iterated at a rapid pace, providing many benefits to human society and garnering increasing attention for smart wearable devices.[1] Meanwhile, with the advancement of nanomaterials, flexible electronics, bioelectronics, and artificial intelligence (AI) technologies, wearable devices are further developing toward lightweightness, flexibility, compactness, and multifunctionality.[2] The prevalence of smartwatches, smart glasses, and health monitoring devices has significantly increased, offering individuals a multitude of conveniences in their daily lives.[3] The rapid advancement of integrated technology has expanded the capabilities of smart wearables beyond their original single-purpose design. Advanced wearable devices now incorporate multiple functions, including energy conversion, sensing, monitoring, wireless transmission, tissue repair, and drug delivery, which have garnered significant interest.[4] However, one of the important challenges for these multifunctional smart wearable devices is ensuring a sustainable energy supply.[5] Traditional batteries encounter challenges such as large dimensions, limited durability, frequent need for replacement or recharging, and negative impact on the environment. These issues restrict the ability to wear gadgets comfortably, limit their usage time, and reduce convenience.[6] By harvesting energy from its working environment without an external power source, self-sufficient energy harvesting (EH) keeps itself operating.[7] The use of this sustainable, renewable energy source offers a solution for powering wearable devices.[8] The human body has the ability to produce energy for wearable devices, making it a potential sustainable energy source.[9,10] In contrast to conventional energy sources, the new energy technology in the form of human-body energy harvesting (hEH) can capture and convert the energy sources from human daily life (e.g., walking, running, finger movement, breathing, pulse beat, body temperature, biochemical reaction, etc.) into electrical energy to meet the energy needs of smart electronic wearables.[11,12] This innovative technology provides new possibilities for the advancement of wearable technology and presents unparalleled prospects for future applications in healthcare, sports and athletics, military operations, environmental monitoring, and other domains.[13]

In this paper, we will explore the current research advances and technological innovations in wearable multifunctional devices (WMDs) based on hEH. According to the EH methods and wearing parts, the innovative materials, structures, and processes involved in the representative studies, as well as the impact on energy harvesting and output, and functional applications are discussed, separately. By reviewing the research progress of WMDs, we reveal that smart wearable devices based on the hEH have

H. Chu, J. Xue, D. Luo, Z. Li
Beijing Institute of Nanoenergy and Nanosystems
Chinese Academy of Sciences
Beijing 101400, China
E-mail: zli@binn.cas.cn

H. Chu, H. Zheng
Department of Anesthesiology
National Cancer Center/National Clinical Research Center for Cancer/Cancer Hospital
Chinese Academy of Medical Sciences and Peking Union Medical College
Beijing 100021, China
E-mail: zhenghui@cicams.ac.cn

J. Xue
School of Medical technology
Beijing Institute of Technology
Beijing 100081, China

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/admt.202302068

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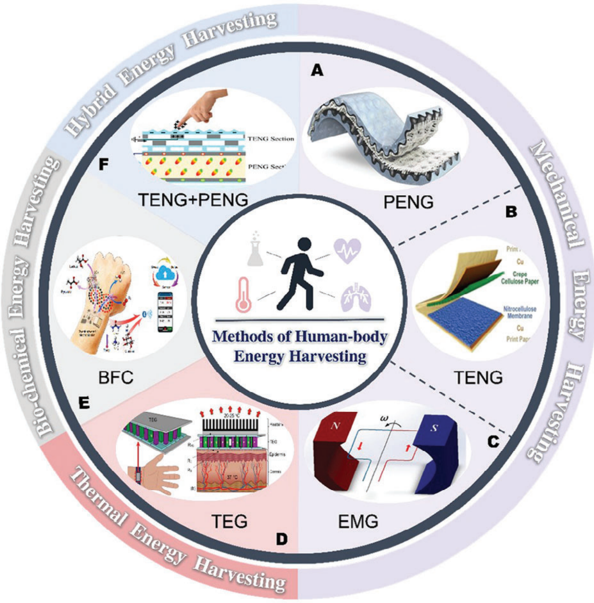

Figure 1. Schematic of various types of wearable multifunctional devices based on human-body energy harvesting. The methods of human-body energy harvesting can be divided into mechanical energy harvesting (piezoelectric energy harvesting A), triboelectric energy harvesting B), electromagnetic energy harvesting C)), thermal energy harvesting D), biochemical energy harvesting E), and hybrid energy harvesting F). Reproduced with permission.[19] Copyright 2017, WILEY. Reproduced with permission.[21] Copyright 2019, Elsevier. Reproduced with permission.[24] Copyright 2014, WILEY. Reproduced with permission.[25] Copyright 2020, Elsevier. Reproduced with permission.[27] Copyright 2020, AAAS. Reproduced with permission.[30] Copyright 2020, American Chemical Society.

become an indispensable part of modern society. In addition, we will discuss the difficulties and limitations facing the area of flexible, wearable devices based on hEH. These challenges involve levels in smart material science, EH and management, AI algorithms, integration techniques, processing and analysis of data, wireless transmission, user privacy, and security.[14] Clarifying these challenges will help researchers, engineers, and policymakers better respond to future development needs and propose solution strategies to drive the development of the next generation of smart wearables.[15] This review aims to provide readers with a comprehensive understanding of this topic, foster greater curiosity and creativity, and together explore the boundless potential of wearable technology in the future.

2. Methods of Human-Body Energy Harvesting

Wearable devices that rely on the hEH are an exciting realm of technology.[16] These devices are designed to harness energy from human mechanical movement, body heat, and other biochemical energy sources to power electronic devices.[17,18] As shown in **Figure 1**, these EH techniques can be classified into several categories, encompassing mechanical EH,[19–24] thermal EH,[25,26] bio-chemical EH,[27,28] and hybrid EH.[29,30] This section covers the research progress of several hEH methods, such as the working principles, material selections, and application scenarios. In **Table 1**, we summarize a series of studies in recent years on WMDs based on hEH.

2.1. Mechanical Energy Harvesting

Mechanical movements and vibrations of the human body, such as running,[31–34] walking,[35–39] arm movements,[40] typing,[41,42] breathing,[43,44] and pulse fluctuations,[45,46] can generate huge amounts of energy. These forms of energy are converted into electrical energy through piezoelectric, electrostatic, friction, and electromagnetic effects to provide a sustainable power supply for low-power electronic devices.[47–51] The emerging EH methods of wearable devices based on human-body mechanical energy include piezoelectric EH,[19,20] triboelectric EH,[21,22] and electromagnetic EH.[23,24] This section focuses on flexible WMDs based on the above EH methods (**Figure 2**).

2.1.1. Piezoelectric Energy Harvesting

Mechanical stress or strain generates an internal electric field in a piezoelectric material, which results in the conversion of mechanical energy to electrical energy, a phenomenon known as the piezoelectric effect.[52] The behavior of electric dipoles in solid materials is the main reason for the piezoelectric effect.[53] In 2006, Prof. Wang et al. pioneered the development of piezoelectric nanogenerators (PENGs) prepared from zinc oxide nanowire arrays based on the piezoelectric effect.[54] PENGs have attracted much attention due to their high energy density, clear physical mechanism, simple structure, low cost, good scalability, and easy application.[55,56] Vibrations and oscillations caused during human activity can be converted into electrical energy by PENGs.[57] Therefore, PENGs are suitable for powering WMDs.

Piezoelectric materials are low-cost, lightweight, and easy-to-control smart materials used in structural actuation.[58] Common inorganic piezoelectric materials are piezoelectric ceramics (e.g., zinc oxide (ZnO),[59] barium titanate (BTO),[60] *lead* magnesium niobate–lead titanate (PMN-PT),[61] and lead zirconate titanate (PZT),[62]) which have high performance but are hard materials, mechanically brittle, and prone to failure even at low strains.[63] This property is not suitable for wearable device applications. However, piezoelectric polymers such as polyvinylidene fluoride (PVDF), parylene C, and polyamide are widely used in the fabrication of PENG-based human mechanical energy harvesters due to their advantages of light weight, low cost, better flexibility, and prolonged stability over time, which allow them to better adapt to the human-body surface structure and conformally attach to the body surface.[64]

In the past few years, the research on PENG-based WMD has been increasing year by year. In order to solve the problem of multi-functional energy consumption, researchers continue to innovate and improve the structure and materials of PENG to improve the output performance and wearability. Recent studies indicate that when PZT is combined with and encapsulated within polymers, it can offer improved stretchability while mitigating its toxicity.[65,66] Inspired by the above research, Wu et al.[67] mixed styrene-butadiene block copolymer (SEBS) and PZT particles in methylbenzene to assemble a highly elastic and stretchable PENG (Figure 2A). They designed the PENG so it could

Table 1. Summary of wearable multifunctional devices based on human-body energy harvesting.

Energy source		Wearing placement	Materials	NG flexibility	Power density	Refs.
Mechanical energy harvesting	Piezoelectric	Wrist, ankle, throat	PZT, SEBS	Stretch: 9.5 times	9.704 mA m−2	[67]
	Piezoelectric	Elbow, wrist, fist, foot, face, throat	P(VDF-HFP) powder, ZnO, Ag		1.37 µW	[68]
	Piezoelectric	Elbow, hip, thigh, knee, ankle	PVDF, BTO, CNT			[72]
	Piezoelectric	Eye	polypropylene electret film, ITO, PET, PDMS	biaxially stretched to 40%		[142]
	Triboelectric	Skin	Silicone EGaIn	300% maximum strain	15 µW	[45]
	Triboelectric	Skin	PDMS PEDOT: PSS	100% maximum strain	3.06 mW m^{-2}	[90]
	Triboelectric	Skin	Cotton fabric PDA CNTs PPy		2.6 W m^{-2}	[92]
	Triboelectric	Skin	Fluoroethylene, copper	FPCB; Over 1000 bending cycles	416 mW m^{-2}	[130]
	Triboelectric	Eye	FEP, ITO, PET			[140]
	Magnetoelectric	Back			0.77 W	[95]
	Magnetoelectric	Joint			0.33 mW	[96]
Thermal	thermoelectric	Skin	Polyacrylamide $Fe(ClO_4)_3/Fe(ClO_4)_2$ graphite paper electrode	1842% strain over 10 times	0.66 mW K^{-2} m^{-2}	[106]
	Thermoelectric	Skin	Gallium indium PDMS	15 000 cycles of 30% tensile strain	650 µW cm^{-2}	[26]
Biochemical energy harvesting	Lactate biofuel cells	Skin	CNT-PDMS MDB-CNT		3.5 mW cm^{-2}	[27]
	Ethanol/oxygen BFC	Skin	3D-NHCAs PI PET		1.01 µW cm^{-2}	[28]
	Lactate biofuel cells	Skin	Au, Co-doped porous carbon electrode		7.2 mJ 80.3 µW	[111]
Hybrid energy harvesting	Triboelectric, perspiration electric	Skin	Ag-coated Cu yarn+ Si-rubber; Super P+ sodium dodecyl benzene sulfonate	Over 150% strain	166 µW cm^{-2}; 5.4 µW cm^{-2}	[131]
	Triboelectric, Sweat based BFC	Skin	PTFE EC/PU CNT-PEDOT: PSS			[18]
	Triboelectric, Magnetoelectric	Skin	PLA Nylon Magnet			[114]
	Triboelectric Piezoelectric	Foot	PTFE, PVDF		77 µW	[153]

be stretched about 9.5 times and had a maximum output current density of 9.704 mA m^{-2}. This PENG-based electronic skin has stretchability, biocompatibility, and versatility, which can respond synchronously and independently to external stimuli like temperature, sound, airflow, and pressure, even under varying stretching conditions. The sensor had a self-powered function, which can power more than 40 LEDs, to a certain extent, solved the limitations brought by battery power to the flexible electronic skin, and promoted the application of flexible PENG in motion monitoring, voice, and posture recognition. In order to improve the output performance of PENG by improving its breathability and hydrophobicity, Fan et al.[68] designed a multi-functional all-nanofiber PENG (ANF-PENG) with ultra-thin, air permeability, super-hydrophobic, and antibacterial properties (Figure 2B). ANF-PENG with sandwich structure is composed of the P(VDE-HFP)/ZnO in the middle as the piezoelectric layer film and Ag@P(VDF-HFP)/ZnO in the upper and lower layers as conductive layers. Then, suture technology was used to stitch the three layers of nanofiber film together as a whole. The nanofiber membrane prepared by using electrostatic direct-writing technology showed good superhydrophobic properties, air permeability, and antibacterial properties, which improved the wearable comfort of PENG. The experimental results indicated that ANF-PENG can achieve an open-circuit voltage of 11.36 V and a maximum power density of 1.37 μW. Also, ANF-PENG had the performance of energy harvesting and storage and the stability of continuous operation. In addition, PENG can not only monitor large limb movements but also monitor muscle movements caused by tiny facial expressions and other actions. It is well known that PVDF is one of the most widely used piezoelectric materials, and the introduction of the electrospinning process promotes the formation of PVDF nanofibers, which have a special porous structure, breathability, large surface-to-volume ratio, and favorable polar phase transformation, and promote the increase of β-phase content and the enhancement of piezoelectric properties.[69–71] Based on this technology, Li et al.[72] used electrospinning to prepare PVDF-based nanofiber membranes, and the tactile sensor designed by them had the characteristics of light weight, air permeability, and self-energy supply (Figure 2C). This PENG device was composed of several functional layers, including an active sensing and electron generation layer made of nanofiber membrane, the conductive layers made of copper, and the protective layers made of PET. Besides, the nanofiber film exhibited strong tactile sensing properties, and the device maintained stability and durability after 12000 loading tests. In addition, the research showed that the PENG device can be attached to multiple parts of the human body and can monitor and recognize human movement.

Although PENGs are highly regarded, integrating PENGs into wearable devices is challenging. Examples include its low level of collected power and the need to convert alternating current (AC), which is in the nature of an instantaneous pulse wave, to direct current (DC). As a result, piezoelectric energy harvesters typically include an AC-DC converter or use non-linear techniques.[73] The wearable PENGs developed so far still require relatively large body movements to generate sufficient energy density. Even though considerable progress has been made, PENG still has relatively small output currents, and increasing their current density is still the main challenge.[74]

2.1.2. Triboelectric Energy Harvesting

Triboelectric nanogenerators (TENGs) are an innovative and environmentally friendly energy technology that converts the tiny, low-frequency mechanical energy generated by human movement into electrical energy to power wearable devices.[13,75–79] TENG was first proposed in 2012 by Prof. Wang, and its operation is based on a combination of the triboelectric effect and electrostatic induction.[80,81] The contact between two triboelectric layers with dissimilar polarities generates the surface electrostatic charge, and an electric field is generated by an external circuit to drive the electrons. To summarize, TENG has the advantages of simple preparation, a wide range of material sources, high power generation efficiency, and environmental friendliness, and has become one of the most widely used methods of harvesting mechanical energy from human movement.

TENGs are currently classified into four operating modes based on polarization direction and electrode configuration (vertical contact mode, single-electrode mode, lateral sliding mode, and freestanding mode).[82–87] Furthermore, for the construction of high-performance TENGs, the selection of triboelectric materials with large differences in electron affinity is critical. Polytetrafluoroethylene (PTFE),fluorinated etheylene propylene(FEP), kapton, and polydimethylsiloxane (PDMS) are the most common electron acceptors, while human skin, glass, nylon, and metals are the most common electron donors. In addition, TENG is more suitable for integration into wearable devices due to its ease of manufacturing at the micro- and nano-level. Photolithographic and soft lithography techniques, electrostatic spinning, irregular micro- or nano-templates, block copolymerization, plasma reactive ion etching, electrochemical anodic etching, and other techniques are commonly employed for the fabrication of triboelectric materials at the micro- and nanoscale.

WMDs based on TENG encounter numerous obstacles. These include the need to enhance the stretchability of devices while maintaining conductivity, as well as improve the comfort and moisture resistance of such devices.[82,88] Several studies have developed devices by considering factors such as material and construction in order to address these challenges. While the conventional approach of introducing conductive particles into elastic substrate materials improves conductivity, it typically results in stress concentration, which in turn reduces the overall ductility and flexibility of the device.[89] Wu et al.[45] employed liquid–metal EGaIn as a flexible electrode and a silicone layer as both an elastic packing layer and a friction layer in order to address this issue (Figure 2D). This WMD possesses excellent tensile qualities, with a capacity to stretch up to 300%. Furthermore, its ability to collect energy in contact separation mode is measured at 15 μW. In addition, this WMD has the capability to detect physiological indicators such as the flexion of joints, cardiac rhythm, and the strength of the wearer's pulse, in elongation and compression modes. Furthermore, outside of considering this matter in terms of materials, it is also a popular approach to improving the flexibility of WMD from a structural design standpoint. Wen et al.[90] developed a TENG with a wrinkled structure, utilizing PEDOT: PSS as the electrode, which is both transparent and stretchy (Figure 2E). A transparent and stretchy TENG with a folded structure was fabricated by applying a conductive PEDOT: PSS film onto a stretched PDMS board. The TENG exhibited excellent conductivity and transparency, along with a maximum strain of 100%. This WMD efficiently harvests mechanical energy from the human body, generating a power output of 3.06 mW m^{-2}. This power is utilized to operate the electronic watch. Additionally, the WMD functions as a very effective sensor for measuring human motion, specifically tracking the frequency of human activity. Furthermore, it showcases its capacity as a high-performing tactile sensor. Due to their reliance on direct skin contact, numerous TENG-based WMDs

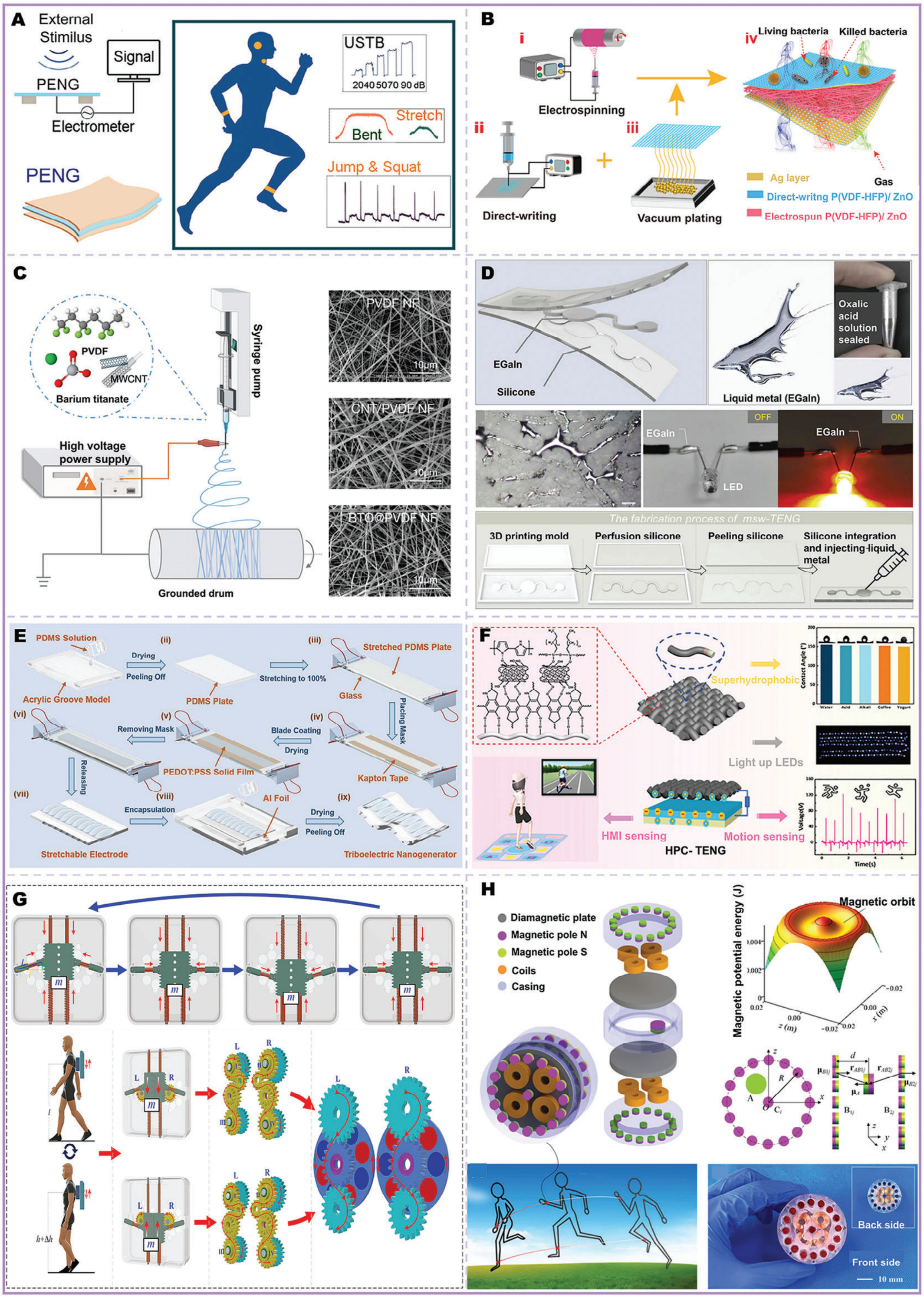

Figure 2. Wearable multifunctional devices based on mechanical energy harvesting. A). Schematic illustration of the working principle of a highly elastic and stretchable PENG. Reproduced with permission.[67] Copyright 2021, American Chemical Society. B). Preparation process of all-nanofiber PENG. Reproduced with permission.[68] Copyright 2023, Springer Nature. C). Preparation of electrospun piezoelectric nanofiber membrane. Reproduced with permission.[72] Copyright 2023, Springer Nature. D). Schematic diagram of the multi-mode stretchable and wearable TENG. Reproduced with permission.[45] Copyright 2022, Elsevier. E). Schematic diagram of fabrication process flow of the stretchable and transparent wrinkled PEDOT:PSS film-based TENG. Reproduced with permission.[90] Copyright 2018, WILEY. F). Schematic diagram of a self-cleaning, wear-resistant, breathable, and hydrophobic TENS. Reproduced with permission.[92] Copyright 2023, American Chemical Society. G).Woking principle of quasi-zero stiffness energy harvesting backpack. Reproduced with permission.[95] Copyright 2023, Elsevier. H). Schematic diagram of a magnetic orbit EMEH. Reproduced with permission.[96] Copyright 2019, AIP Publishing.

that harvest human body energy, necessitate enhanced comfort, durability, and moisture resistance.[91] He et al.[92] constructed a TENG-based WMD that is self-cleaning, wear-resistant, breathable, and hydrophobic (Figure 2F). The conductivity and frictional positive electrode qualities of cotton fabric are enhanced by applying polydopamine, carbon nanotubes, and polypyrrole onto its surface. Subsequently, hexadecyltrimethoxysilane was chosen for hydrophobic alteration in order to make the material suitable for moisture-resistant conditions. The proposed TENG exhibits a significant enhancement in performance compared to the unmodified fabric-based TENG. The superhydrophobic and conductive composite fabric-based TENG achieves a performance boost of ≈7.2 times, with a maximum power density of 2.6 W m^{-2}. This improvement can be attributed to the presence of strong electron-donating groups, high conductivity, and abundant micro/nano structures.

Although TENGs are widely used in WMDs, they still face many drawbacks. The energy conversion efficiency of TENG is relatively low, and part of the mechanical energy is lost in the form of heat energy. To enhance the performance, researchers have improved the structure of TENG using micro-nano fabrication techniques and precision fabrication, which raises the preparation challenges. In addition, the material selection of the TENG is crucial, which will have a large impact on the durability and output performance of the TENG. The frequency dependence of the TENG also limits its applicability in various settings. Thus, the stability, reliability, and environmental tolerance of TENG-based WMDs are still issues that need to be further overcome.

2.1.3. Electromagnetic Energy Harvesting

The electromagnetic energy harvester (EMEH) is the main power generation equipment in human society. EMEH is designed based on the basic principle of electromagnetic induction. EMEH consists of both a magnet and an induction coil, which can generate induced voltage.[93] As a voltage source, the output voltage of the EMEH depends on the magnetic induction intensity, determined by the intrinsic properties of the material. The size of the permanent magnet, the number of turns for the coil, and the cutting speed also affect the output voltage.[24] Permanent magnets are made of ferromagnetic or ferrimagnetic materials, which retain their magnetic properties even after magnetization. EMEHs have the advantages of low internal resistance, simple structure, high current density, and easy processing compared to other types of energy harvesters. However, given the inherent features of low-frequency (≤5 Hz), and random and irregular vibrations during human mechanical motion, the human-body mechanical energy based on EMEH is not as desirable as other generators. Hence, optimizing the coil–magnet structure and increasing the rate of cutting flux can improve the energy harvesting efficiency.[94] Li et al.[95] constructed a bistable quasi-zero stiffness structure by combining two positive stiffness springs and two negative stiffness springs in parallel (Figure 2G). This design facilitates the collection of low-frequency human mechanical energy by the system. Simultaneously, by employing structural design, bidirectional vibration can be transformed into unidirectional high-speed rotation, enhancing the efficiency of electromechanical conversion. The device is designed to be compatible with standard backpacks, allowing an electromagnetic generator (EMG) to efficiently harvest low-frequency human motion energy. While jogging, a power conversion of 0.77 w was attained, confirming the potential of this wearable mobile device for generating emergency power during outdoor activities. Zhao et al.[96] introduced a magnetic track EMEH that efficiently organizes multiple magnetic fields on a circular and uniform track (Figure 2H). This arrangement enables a magnet to move consistently along the track, propelled by irregular low-frequency human mechanical energy. Consequently, the device effectively converts human mechanical energy into electrical energy. The device has been validated by both theoretical analysis and experimental testing to effectively gather low-frequency energy. It is capable of harnessing energy from walking and running, yielding a power output of up to 0.33 mW.

However, EMEH-based WMDs still face numerous challenges, such as limitations in energy conversion efficiency and performance due to device size constraints, and the manufacturing process of micro-nano scale is more complicated. Because of the irregularity and low frequency of human-body motion, it also increases the difficulty of harvesting human-body energy based on EMEH. With the deepening of research, the hEH technology based on EMEH is expected to be improved to further achieve high efficiency and miniaturization. At the same time, we can further explore how this technology can be applied to various WMDs, including health monitoring devices, virtual reality devices, and exercise trackers. In conclusion, future research and technological improvements are expected to advance the field and make wearables more accessible and practical.

2.2. Thermal Energy Harvesting

In addition to releasing energy in the form of motion, a large amount of human energy is released in the form of heat. Therefore, the technology of collecting human heat using thermoelectric harvesters has become one of the hot spots in many studies.[97] The average human core body temperature is ≈37 °C, making it an available and sustainable kind of green energy.[98] Human beings are warm-blooded creatures, and there is a temperature difference with the external environment, which can produce heat exchange.[99] Thus, relatively small amounts of body heat energy can be constantly converted into usable power using thermoelectric generators (TEGs) or pyroelectric generators (PEGs).[98,100,101]

Using the Seebeck effect, TEGs convert waste heat into electricity and are attracting interest as a potential EH technology.[102] The Seebeck effect is attributed to carrier motion within the semiconductors, i.e., the diffusion of electrons and holes caused by temperature gradients.[103] Furthermore, PEGs are another form of thermal energy harvester based on the pyroelectric effect.[104] Crystals with inherent polarization properties exhibit a change in spontaneous polarization strength when heated or cooled, resulting in the generation of surface-polarized charges in a specific direction of the crystal.[105] Compared with mechanical EH technology, the thermoelectric harvester is a passive energy collecting technology. Thanks to a stable source of energy, the two thermoelectric harvesters mentioned above can use the heat generated by human metabolic activity to continuously power WMDs in an

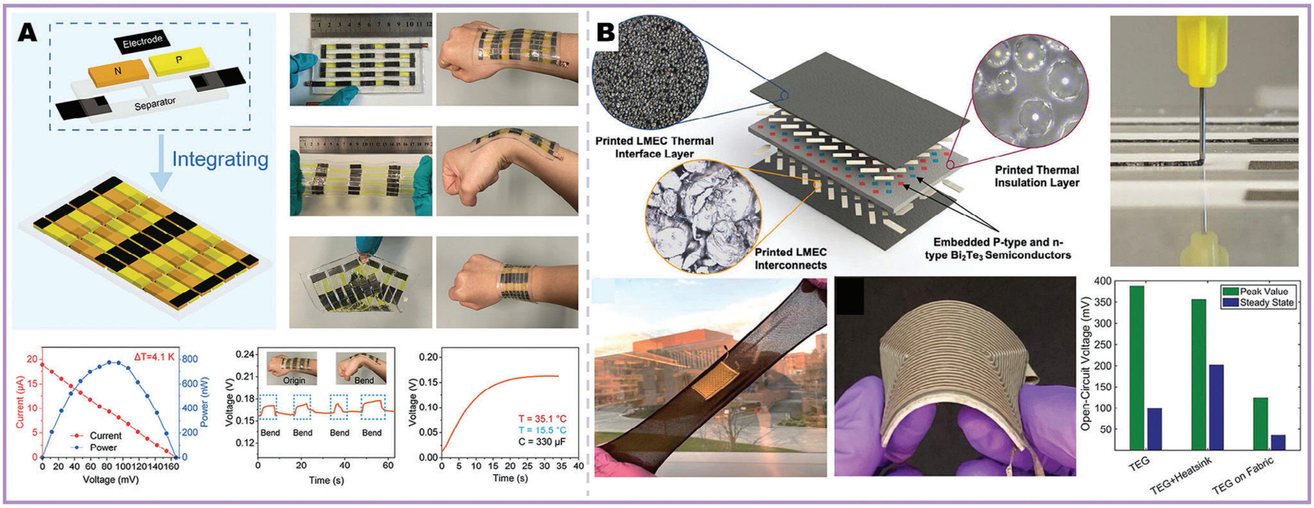

Figure 3. Flexible wearable multifunctional devices based on human-body thermal energy harvesting. A). Illustration of wearable hydrogel thermocell for energy harvest. Reproduced with permission.[106] Copyright 2018, WILEY. B). Wearable TEGs via 3D printing of multifunctional elastomer composites. Reproduced with permission.[26] Copyright 2022, WILEY.

almost permanent manner without requiring any movement of the human body.

The development of thermoelectric energy harvesters from rigid and bulky to flexible and lightweight is a result of advancements in material science and processing technology. Materials such as inorganic films, organic compounds, organic–inorganic hybrid materials, conductive polymers, and liquid metal composite materials are frequently chosen for thermoelectric energy harvesters. Xu et al.[106] developed a TEG that integrates the superior thermoelectric properties of inorganic materials with the flexible attributes of organic materials (**Figure 3A**). This TEG utilizes a hydrogel composed of polyacrylamide that functions as both a highly elastic and flexible substrate as well as a matrix for non-isothermal redox reactions. Graphene paper electrodes are utilized to create a thermoelectric-based WMD that can easily adapt to the contours of the human body. The single p-n cell has a maximum power density of 0.66 mW K^{-2} m^{-2}, which proves that employing the flexible TEG to monitor human activities in daily scenarios is possible. Contrary to solid conductive coatings, liquid metals possess the advantageous ability to deform easily in wearable devices.[107] Additionally, liquid metals exhibit excellent thermal conductivity, hence improving the thermal management of TEG.[108] Han et al.[26] presented a high-performance TEG that utilizes liquid metal created by 3D printing technology (Figure 3B). Utilizing elastomeric composite ink for printing the thermal interface layer, insulation layer, and connecting elements exhibits commendable flexibility and durability. In addition, elastomeric composites containing small microspheres are developed to create a printable, flexible, and lightweight thermal insulator for the device. The TEG, which has been specifically engineered for optimal performance, demonstrates efficient energy harvesting capabilities with a power density of 650 μW cm^{-2} when exposed to a temperature gradient of 60 °C. Furthermore, it has been confirmed that this TEG holds promise for use in human–computer interaction.

Despite the importance of thermal EH technology in hEH and power supply for WMDs, there are still a few key issues that need to be addressed. The primary constraint of thermal EH technology is its reliance on large temperature differences; nonetheless, the small range of temperature differences between the human body and the environment restricts the output power of this harvesting method. In addition, TEGs have a complex structure and high cost, while PEGs have fewer application scenarios for human-body thermal EH, are susceptible to environmental interference, and have a slow response time. Furthermore, the exploitation of thermoelectric conversion materials with high Seebeck coefficients and pyroelectric materials with high pyroelectric coefficients is still a top priority.

2.3. Biochemical Energy Harvesting

The human body contains abundant chemical energy that can be used as an ideal energy source for biofuel cells (BFCs). BFC is mainly divided into enzyme-catalyzed fuel cells, and microbial cell-catalyzed fuel cells.[109] The primary area of study in biochemical EH is enzyme-catalyzed fuel cells from the perspectives of biosafety and energy conversion efficiency. BFCs using enzymes as catalysts can convert the biochemical energy of the human body into electrical energy. There are a variety of substances in human-body fluids (such as sweat and tear), and researchers use either endogenous (glucose,[110] lactic acid[27,111]) or exogenous (ethanol[28]) substances as biofuels to generate electricity. Lactic acid, for instance, is easily oxidized by oxidizing enzymes (lactate oxidase or lactate dehydrogenase) and is relatively abundant in sweat (in the millimolar range). In conclusion, BFCs have the advantages of a diverse range of substrate sources, mild reaction conditions, and a wide range of catalysts. Thus, BFC holds the potential to serve as an excellent fuel source for self-powered WMDs.

Endogenous chemicals, such as glucose and lactate, present in human fluids, can serve as biofuels for generating power. Guan et al.[111] developed a comprehensive system for sweat collection, including wearable modules, storage supercapacitor modules,

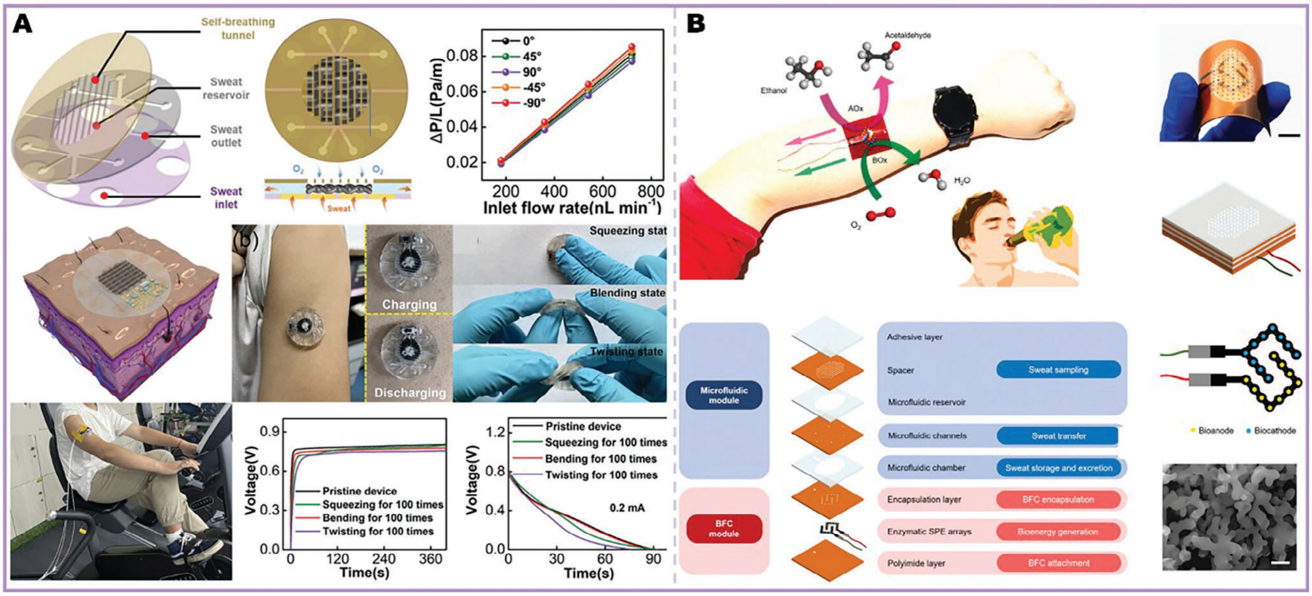

Figure 4. Wearable multifunctional devices based on human-body biochemical energy harvesting. A). Schematic diagram of the supercapacitor–biofuel cell microfluidic device. Reproduced with permission.[111] Copyright 2023, WILEY. B). Diagram of the flexible and wearable epidermal ethanol biofuel cells for on-body, real-time bioenergy harvesting. Reproduced with permission.[28] Copyright 2021, Elsevier.

and biofuel cell microfluidic modules (**Figure** 4A). The complete system harnesses and stores energy by extracting lactic acid from perspiration, achieving energy and power outputs of 7.2 mJ and 80.3 mW, respectively. Moreover, the entire system exhibits commendable resilience. Furthermore, given the wide range of human compounds, certain exogenous substances also function as energy sources. Sun et al.[28] developed a flexible wearable biofuel cell that incorporates a microfluidic module to collect, transfer, and store sweat (Figure 4B). They used this module to transport sweat to the ethanol/oxygen BFC, enabling real-time energy collection from sweat and facilitating the absorption of ethanol. This innovative design allows for a non-invasive and flexible exogenous BFC. The efficacy of BFC, which relies on sweat collection, is significantly influenced by the secretion status of sweat. Hence, it is imperative to efficiently gather and retain sweat energy.

The availability of fuels such as human sweat limits the output and application scenarios of. In addition, the use of endogenous substances in human sweat (glucose, lactic acid, etc.) as fuel for continuous energy conversion, and the impact on the homeostasis and biosecurity of healthy people or diabetic people is still a problem that needs to be explored.

2.4. Hybrid Energy Harvesting

The efficiency of the energy harvester with a single EH method is low, which limits the functional expansion of smart wearable devices. With the continuous improvement of people's needs and technological advancement, hybrid energy collectors integrating a variety of EH methods have realized the complementary advantages of each collection method, further improving energy conversion efficiency, reducing energy waste, and expanding the application market.[112,113] A multimodal energy harvester can comprise an integration of devices designed to capture diverse forms of energy or devices intended to harness the same type of energy through distinct mechanisms. Next, we review and summarize these WMDs based on hybrid EH technology.

Wang et al.[18] presented the notion and design concepts of electronic textile microgrids through the exhibition of a multimodule bioenergy microgrid system (**Figure** 5A). An electronic textile microgrid was developed that exclusively depends on the collection of human energy. This is achieved through the utilization of sweat-based BFC and TENG to gather biochemical and mechanical energy from everyday activities. The collected energy is efficiently stored in supercapacitors to successfully power various wearable applications.

The human body commonly experiences sweating during periods of vigorous physical activity. Therefore, harnessing mechanical energy generated during exercise to power a sweat monitoring device is an optimal approach. Gai et al.[114] developed a self-powered wireless wearable device for analyzing sweat (Figure 5B). This system enhances the effectiveness of harvesting mechanical energy from human activities by integrating TENG with EMG. Additionally, it incorporates a low-power power management module and low-power Bluetooth, enabling the gathering of energy from the sporadic low-frequency mechanical energy generated by the human body and the wireless tracking of sweat markers.

Overall, flexible, wearable devices based on hEH have great potential to provide autonomous power to electronic devices. Different EH methods have their own advantages and limitations, so the choice for a particular application should be based on device requirements, user behavior, and feasibility. In the future, with the continuous development of integrated technology and material science, these energy collectors are expected to be more widely used in daily activities, movement monitoring, health diagnosis and treatment, military training, and other fields.

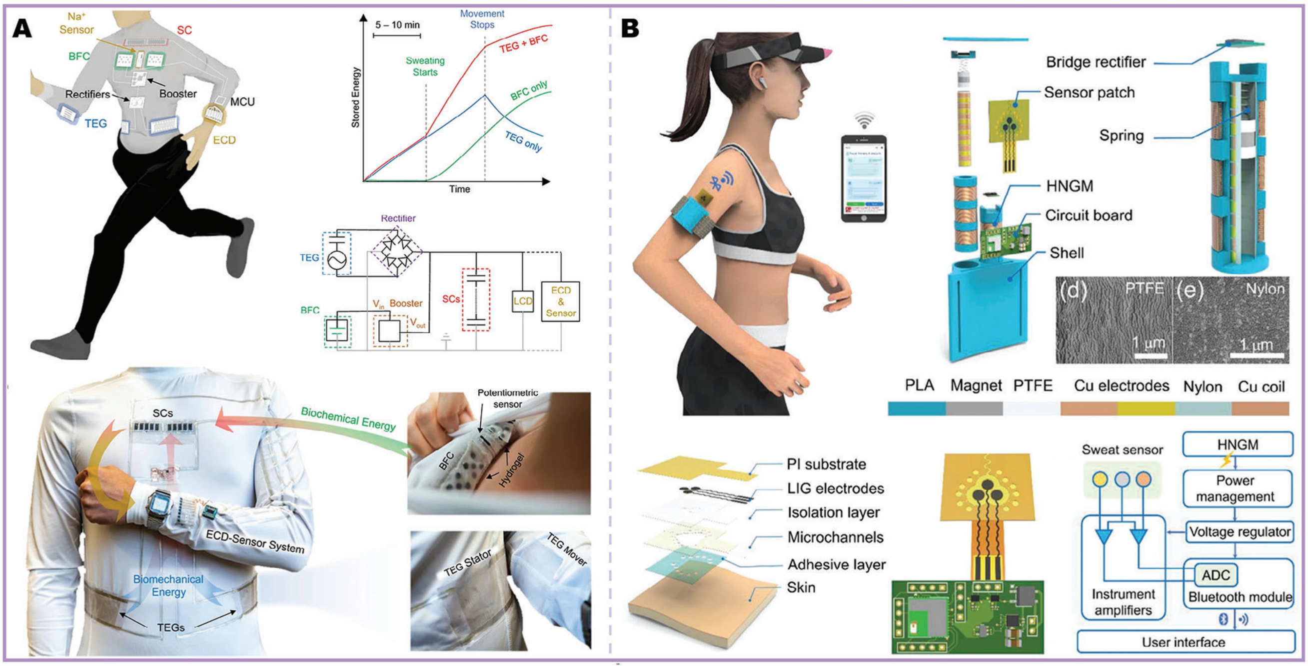

Figure 5. Wearable multifunctional devices based on human-body Hybrid energy harvesting. A). Design and concept of the multi-modular energy microgrid system. Reproduced under the terms of the CC-BY license.[18] Copyright 2021, The Authors, published by Springer Nature. B). Schematics of the self-powered SWSAS for wireless molecular monitoring. Reproduced with permission.[114] Copyright 2022, WILEY.

3. Wearable Formats of WMDs

The vital functions of the human body are carried out through the processes of material metabolism and energy conversion.[115,116] A portion of the energy obtained from food is stored in compounds like fat and glycogen, while the bulk is transformed into different types of energy to sustain physiological processes and life activities, such as mechanical energy, thermal energy, biochemical energy, and so on.[11,117,118] This aspect of energy offers benefits such as safety, reliability, and environmental friendliness. The research on wearable multifunctional electronic devices that harness human energy has gained significant attention. These devices come in various forms, such as eye masks and contact lenses for the eyes, electronic skin or tattoos and conductive textiles attached to the skin, exoskeleton systems worn at the joints, and intelligent shoes and socks for the sole of the foot (**Figure 6**). Self-powered sensor technology has enabled the development of WMDs that may perform purposes such as monitoring human health and facilitating human–computer interaction.[54,119] As an emerging hot technology, self-powered sensors refer not only to devices that generate energy as a power supply by capturing external energy, but also to devices that can directly convert external energy into electrical signals as output.[120,121] Self-powered WMDs have the capability to gather, convert, and utilize energy generated by the human body, such as mechanical and thermal energy, into electrical energy. This electrical energy is either a power supply or directly serves as the output of the system in the form of electrical signals. This chapter will present various self-powered WMDs, focusing on their wearable format.

3.1. Skin-Based WMDs

The skin, which envelops the majority of the body, is the biggest organ in the human body.[122,123] Hence, it is the most advantageous position for wearable electronic devices to operate.[124,125] Thanks to the large contact surface with the skin, such wearable devices make it easier to achieve multiple functions. Wearable WMDs that utilize human skin can gather mechanical energy from human movement as well as thermal and biochemical energy from the skin. These devices can then transfer this energy to bioelectronic devices that are employed to monitor various physiological and biochemical indicators.

Sweat contains a variety of substances, and the use of sweat monitoring in WMDs enables non-invasive metabolic testing and disease detection.[126,127] Simultaneously, perspiration serves as an effective and environmentally-friendly bioenergy source for the functioning of WMDs.[128,129] Gao et al.[27] developed a skin-based WMD that harvests energy from perspiration and analyzes its constituents to assess human health (**Figure 7A**). The self-powered e-skin is designed to have a modulus that closely matches that of human skin, allowing it to fit snugly and greatly enhancing its sensing accuracy. Simultaneously, the lactate BFCs included in it can reliably and consistently harvest energy from perspiration, achieving a power output of up to 3.5 mW cm^{-2}. Additionally, it tracks important metabolic indicators such as glucose and pH levels in sweat and then sends this data to distant viewing interfaces using low-energy Bluetooth technology. And the WMD has the capability to observe the condition of muscle contraction and is anticipated to function as a human–machine interface for prosthetics.

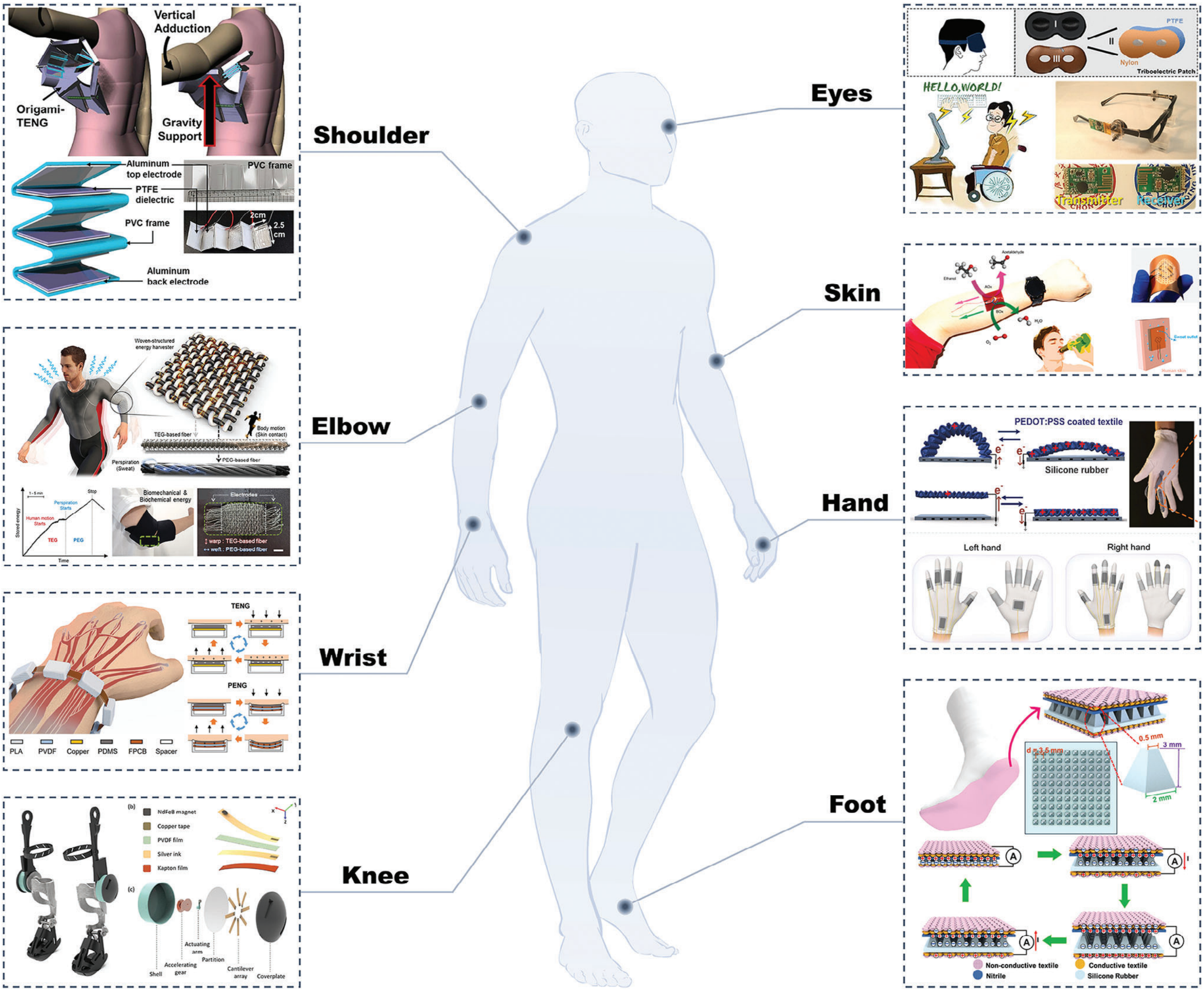

Figure 6. Current wearable forms and applications of wearable multifunctional devices based on human-body energy harvesting. Reproduced with permission.[157] Copyright 2022, Elsevier. Reproduced with permission.[131] Copyright 2023, WILEY. Reproduced with permission.[146] Copyright 2022, WILEY. Reproduced with permission.[155] Copyright 2022, American Chemical Society. Reproduced with permission.[138] Copyright 2022, American Chemical Society. Reproduced under the terms of the CC-BY 4.0 license.[140] Copyright 2017, The Authors, published by AAAS. Reproduced with permission.[28] Copyright 2021, Elsevier. Reproduced with permission.[147] Copyright 2019, Elsevier. Reproduced under the terms of the CC-BY license.[151] Copyright 2021, The Authors, published by Springer Nature. Reproduced under the terms of the CC-BY license.[154] Copyright 2020, The Authors, published by Springer Nature.

Gao et al.[130] introduced a robust, mass-produced, and self-powered wearable electronic skin to enhance the monitoring of human health during physical activity (Figure 7B). The WMDs efficiently harness energy from human motion using a free-standing mode triboelectric nanogenerator (FTENG) that relies on flexible printed circuit boards. The meticulously engineered FTENG exhibits a substantial power output of ≈416 mW m^{-2}. By integrating systems seamlessly and implementing efficient power management, the system is capable of converting human mechanical energy into electrical energy. Additionally, it can wirelessly send the biochemical indications present in sweat during movement to the user interface via a Bluetooth module.

The efficacy of skin-based WMDs is frequently influenced by the level of system breathability and humidity. Song et al.[131] developed a fabric that can harvest energy and is both stretchable and washable (Figure 6). By weaving TENG-based fibers with respiratory electric generator-based fibers, it is possible to simultaneously harvest energy from the wearer's movements during exercise and utilize sweat from the skin to produce electrical energy, and the highest power output of these fibers is 166 and 5.4 μW cm^{-2}, respectively. This WMD is ingeniously engineered to minimize the influence of skin perspiration on the electrical functioning of the device while simultaneously enhancing the effectiveness of EH. Upon integration with capacitors, it effectively energizes Internet of Things (IoT) devices and more than 100 LEDs.

Aside from the structural characteristics of thin films and fabrics, there are other types of self-powered skin-based WMDs,

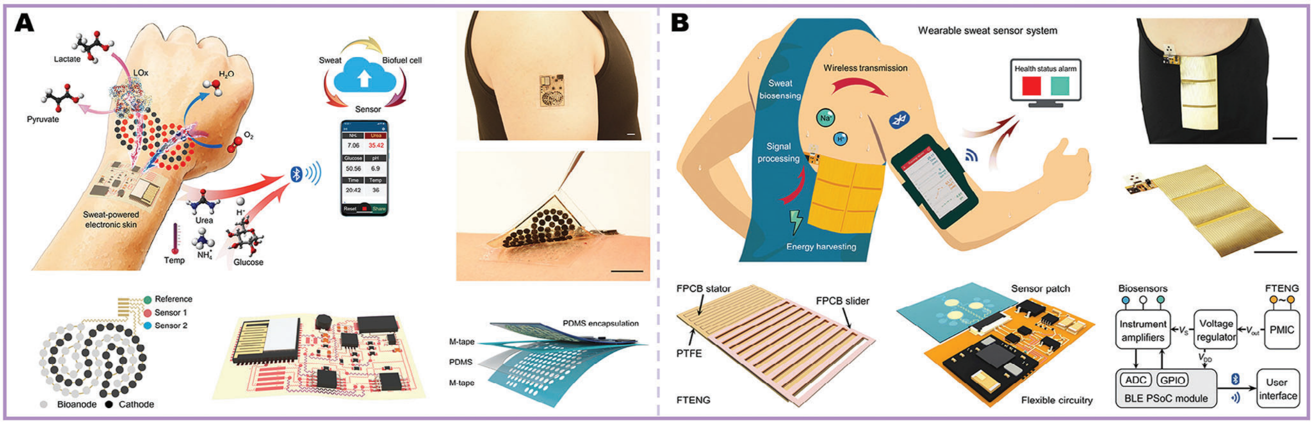

Figure 7. Wearable multifunctional devices based on skin. A). Perspiration-powered soft electronic skin (e-skin) for multiplexed wireless sensing. Reproduced with permission.[27] Copyright 2020, AAAS. B). Battery-free FWS^3 for wireless and noninvasive molecular monitoring. Reproduced under the terms of the CC-BY license.[130] Copyright 2020, The Authors, published by AAAS.

such as microneedles[132–134] and electronic tattoos.[135–137] They can also gather mechanical, thermal, or biochemical energy in order to accomplish tasks such as delivering medication and monitoring physiological signals.

3.2. Eye-Based WMDs

The human eye is a relatively energy-rich part of the body, and its own energy comes from eye movements, blinking, and other physiological activities, which provide feasibility for ocular EH. For the physiological structural characteristics of the eye, the existing wearable forms include eye masks, eyeglasses, contact lenses, and so on. The eyepatch captures the mechanical and thermal energy generated by physiological activities such as blinking and eye movements and converts it into electrical energy to power WMDs. Since the eyepatch is worn around the periphery of the eyes, it is lightweight and comfortable for long periods. Contact lenses are one of the most popular eye-based wearable devices. They can be in direct contact with tears, the internal chemicals of the eyes, and the external air for hours without severe irritation, which can provide a unique platform for continuous monitoring of physiological information and environmental conditions. Tears, as a type of body fluid, contain a wealth of biomarkers, and their detection is a non-invasive test that can be a beneficial alternative for disease diagnosis and treatment. Overall, the self-powered WMDs based on human eyes are lightweight, highly sensitive, flexible, portable, and easy to monitor physiological data and provide real-time feedback. They are now widely used in the fields of intraocular pressure monitoring, eye movement sensing, sleep monitoring, augmented reality and virtual reality (VR) experiences, tear analysis, vision correction, and the treatment of eye diseases.[138–140]

The cornea acts as a protective barrier against external threats, rendering it vulnerable to infection and harm. Corneal damage is a prevalent eye illness, and it is essential to preserve the integrity and transparency of the cornea to restore eyesight.[141] Utilizing endogenous electric fields is regarded as a highly efficient approach for the restoration of corneal injuries. Yao et al.[142] drew inspiration from snowflakes and created a piezoelectric contact lens, following this idea (**Figure** 8A). The structural design and performance optimization can achieve optimal mechanical flexibility, while converting the energy from subtle blinking movements into pulsed electric fields without obstructing the line of sight. This intervention effectively aids in repairing corneal damage. Therapeutic validation was conducted on corneal injury models in mice and rabbits.

The electrooculogram signal is a feeble bioelectrical signal, constrained by its low signal-to-noise ratio, inadequate stability, and challenges in its acquisition and application.[143] The mechanical movement of the skin at the temples exhibits greater sensitivity and stability as compared to the electrical signals of the eye during blinking. Hu et al.[140] introduced a transparent and flexible sensor utilizing TENG technology (Figure 8B). This sensor is incorporated into spectacles and is capable of converting mechanical impulses generated during blinking into high-level electrical signals. The effective implementation of wireless transmission modules has enabled intelligent control of domestic appliances and other operations, showcasing significant potential in applications involving human–computer interaction.

Despite the numerous benefits of self-powered eye-based WMDs, the human eye is a delicate organ, and the wearing device must be safe and clean enough to ensure that it does not cause damage to vision, ocular tissues, or the eyeball. The material of the spectacle lens should be selected for wearing comfort, softness, ergonomics, and non-breakable biocompatible materials. In addition, the small space of the eye to integrate multifunctional modular units in small lenses increases the complexity of preparation and design. Additionally, there are fatigue limitations in eye movements or fixation behaviors that may limit the function and performance of WMDs. More generally, there is often a cautious and conservative attitude toward technologies and interventions involving the eyes, and thus eye-based, self-powered WMDs will face social acceptance issues.

3.3. Hand and Wrist-Based WMDs

Human hands are some of the most intelligent organs in the body. In millions of years of evolution, the human hand

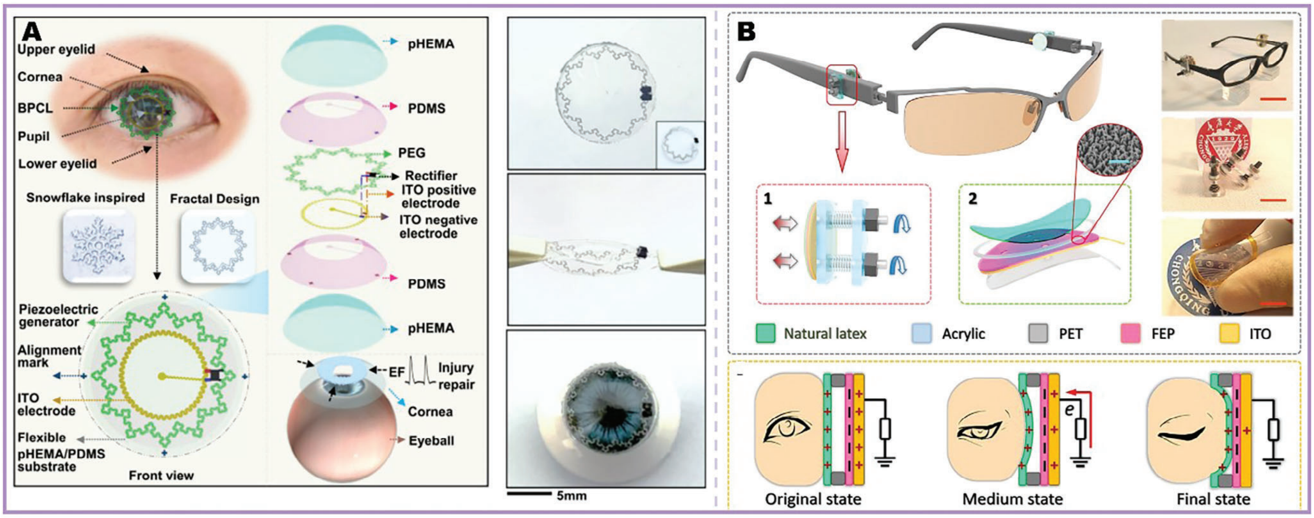

Figure 8. Wearable multifunctional devices based on eye. A). Schematics of the overall snowflake-inspired BPCL structure and exploded illustration of the device components, essential materials, multilayer structures, and repair mechanism. Reproduced under the terms of the CC-BY license.[142] Copyright 2023, The Authors, published by Springer Nature. B). Schematic structure of a pair of ordinary glasses mounted with msTENG. Reproduced under the terms of the CC-BY license.[140] Copyright 2017, The Authors, published by AAAS.

developed into the most flexible, dexterous tool in the world. Among the many functions and meanings of the human hand, it is the channel by which information is expressed and can perform fine activities such as pinching and squeezing. Meanwhile, the finger is a highly sensitive part of the body to touch. Touching objects enables us to recognize their shape, temperature, texture, hardness, etc., allowing us to interact with them. Individuals with hearing and speech challenges, in particular, often use fingers to communicate in sign language, which is an essential form of expression. It is particularly important to mention that fine and complex movements of the hand are dependent on the stability and flexibility of the wrist. Hands and wrists are complex and closely related systems that cooperate to perform a variety of functions. Based on the above important significance, researchers have created WMDs attached to the hands and wrists that can use a rich variety of hand movements and features to realize various interactive functions. Common wearable forms of such devices include smart gloves, finger cuffs, rings, smartwatches, wristbands, and so on. For instance, smartwatches and wristbands make full use of the characteristics of the wrist tissue structure to fully obtain the pulse, blood pressure, and other physiological signals for cardiovascular disease prevention and monitoring.[144,145] Wrist-based WMDs are also used in VR, enabling applications such as gesture command recognition and disability assistance.[146] Overall, hand- and wrist-based WMDs are convenient, self-adaptive, powerful, and responsive. They are widely used in the fields of virtual and augmented reality, remote control, health monitoring, and rehabilitation therapy.[147,148]

Complex muscle groups govern the delicate movements of the hand. By monitoring the mechanical data of the epidermal muscles, one can discern the hand's movements and deduce various gestures.[149] Tan et al.[146] developed a wristband for gesture recognition that utilizes a self-powered coupled force electric sensor, which includes eight channel TENGs and PENGs (**Figure 9A**). Following various gestures made by the wearer, the muscles on the outer layer of the skin experience mechanical deformation, which is subsequently transformed into electrical impulses via force-electric sensors. The machine learning system, utilizing eight channels of electrical signal output and employing a linear discriminant analysis model, has successfully accomplished word-for-word recognition of sign language actions, achieving an impressive recognition rate of 92.6%.

Currently, the technology for accurately identifying basic movements using machine learning and wearable sensors has reached a state of full development. However, the majority of these works are limited to basic words, numbers, and letters, and are unable to accomplish instantaneous translation of whole sign language phrases. This limitation continues to present issues in effectively addressing daily language communication hurdles.[150] Lee et al.[151] conducted research on a glove that can recognize sign language using AI and VR technology (Figure 9B). The glove incorporates TENG sensor arrays to detect motion in 15 crucial areas of the hands, such as fingers, knuckles, wrists, palms, and other regions. By utilizing sensors to extract electrical signals, the smart glove system was able to achieve precise recognition of 50 individual words and 20 complete phrases. This recognition was accomplished through the implementation of machine learning-based word segmentation. Simultaneously, the technology has the capability to transmit the translated utterances to a virtual reality setting and exhibit them as written text. Typing enables non-sign language users to engage in real-time, two-way conversations with sign language users.

Despite the strong functionality and development potential of hand-based WMDs, technical barriers must still be overcome, such as the need to improve the device's anti-interference capability against motion noise and other interference during command execution by hand, as well as to optimize smart device accuracy and stability. Improving adaptability for various users remains a challenge due to significant variations in the size, form, and mobility of their hands. As well, the finger involves the privacy of

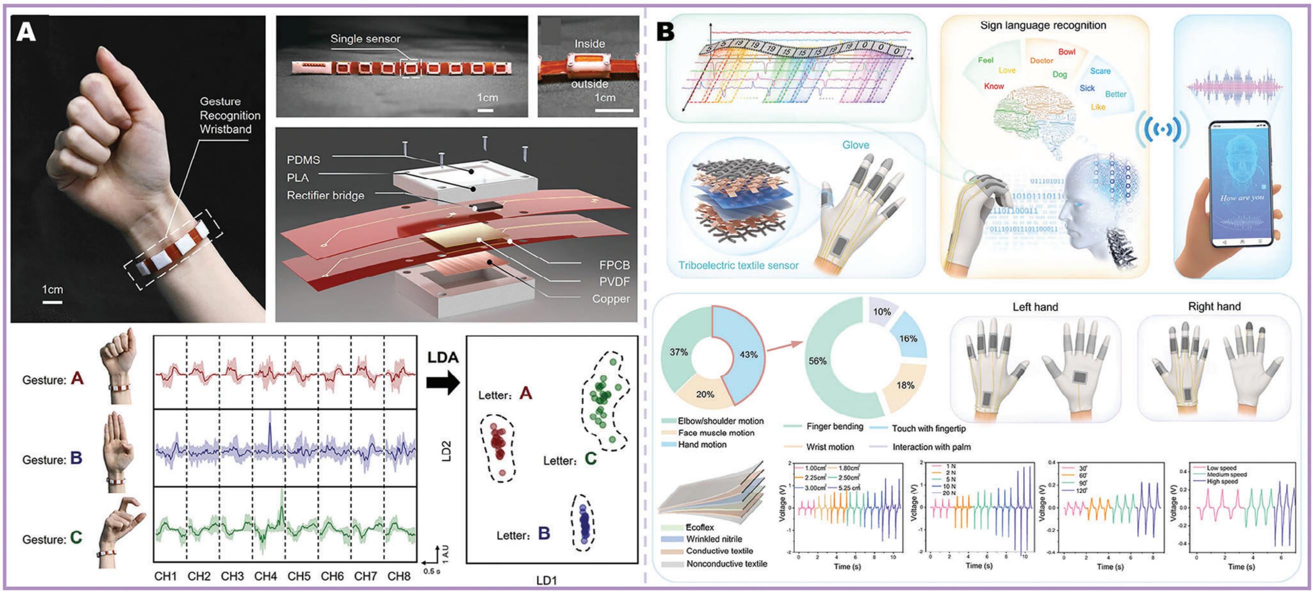

Figure 9. Wearable multifunctional devices based on hand and wrist. A). Overview of gesture recognition wristband. Reproduced with permission.[146] Copyright 2022, WILEY. B). The glove configuration and sensor characterization. Reproduced under the terms of the CC-BY license.[151] Copyright 2021, The Authors, published by Springer Nature.

the user, and the related information security work must be taken seriously.

3.4. Feet-Based Wearable Devices

Human feet are an important source of movement for the body. When walking, the feet detect the ground and coordinate their own bones, joints, and muscles to maintain balance in the body. It is during the resting support period that the rigid and elastic structures of the feet act as cushions, transitions, and rigid levers, respectively. It is well known that the human body generates endless amounts of mechanical energy during other activities such as walking, running, and so on, which can be captured by mechanical energy converters and converted into electrical energy to power portable WMDs. In existing research designs, shoes, socks, insoles, and ankle loops are the most common forms of wearing. Long lifespan, green environment, comfort, and ease of wear are some of the advantages of these devices. At present, it is mainly used to monitor human gait, walking mode, steps, walking speed, dorsalis pedis arterial pressure, sweat detection, sports injuries, and other biochemical indicators. And beyond that, rehabilitation, restoring foot function, and improving quality of life can also be achieved with these devices.

The utilization of biomechanical energy for powering wearable electronic devices has demonstrated significant potential in the realm of the IoTs.[152] Du et al.[153] developed a shoe insole-shaped composite nanogenerator by integrating multi-layer TENG and arched PENG technologies (**Figure** 10A). This WMD serves a dual purpose. It functions as a harvester, converting the mechanical energy generated by footsteps into electrical energy. Additionally, it acts as a sensor capable of discerning three distinct types of motion: walking, stepping, and jumping. The real-time detection of the pulse signal of the dorsal foot artery is done by simultaneously coupling it with a self-powered monitoring device. The intelligent insole can generate a maximum open circuit voltage of 150 V and a short circuit current of 4.5 μA when the wearer is in motion. Following an 8 min walk, this WMD has the capability to charge a 100 μF capacitor to a voltage of 2.5 V. The incorporation of energy collection, storage, and use in a unified design holds significant potential for future applications in self-powered monitoring and intelligent analysis of lower limb blood supply for professional sports.

The gait information encompasses valuable data pertaining to health state and distinctive traits, thereby indicating promising potential for the utilization of WMDs for gait detection. In comparison to smart insoles, socks offer greater flexibility and a broader range of potential applications. Zhang et al.[154] created smart socks using TENG, which enables continuous monitoring of the human body's state over an extended period of time (Figure 10B). The WMD has the ability to convert mechanical energy into electrical energy during low-frequency movements in order to power Bluetooth. Additionally, they can detect signals such as body temperature and pressure, enabling gait recognition and showing promising potential for use in smart homes and virtual reality interactions.

3.5. Musculoskeletal System-Based Wearable Devices

The musculoskeletal system of the human body consists of bones, skeletal muscles, and joints, which is a typical multi-flexible body system with a wide range of relative motion and deformation coupling dynamics. The human body is rich in mechanical energy in the process of activity; through wear in the bones, muscles, and joints of the self-sufficient device, this energy can be converted into mechanical energy and electrical energy for intelligent electronic devices. This passive device that

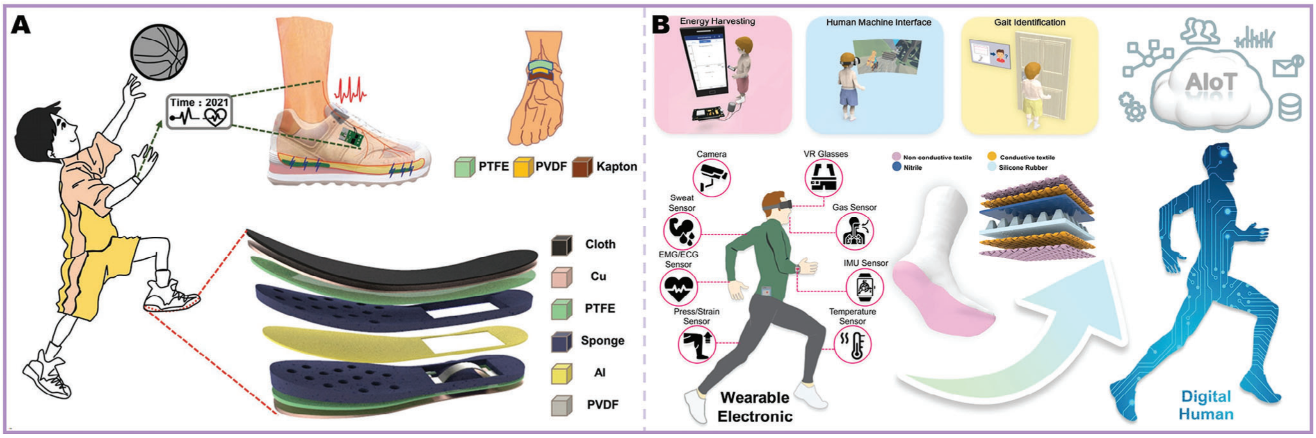

Figure 10. Wearable multifunctional devices based on feet. A). Overview diagram of the self-powered dorsalis pedis artery monitoring system based on the insole hybrid nanogenerator. Reproduced with permission.[153] Copyright 2022, WILEY. B). The schematics and future prospects of the deep learning-enabled socks. Reproduced under the terms of the CC-BY license.[154] Copyright 2020, The Authors, published by Springer Nature.

attaches to the musculoskeletal system greatly reduces the size and weight of the device, making it easier to operate. Common forms of wearables are exoskeletons, patches, shoulder belts, and many other diverse forms. A wearable exoskeleton system is composed of a variety of sensors, actuators, mechanical structures, and control systems.[155] As musculoskeletal system-based WMDs have the advantages of fine sensing, flexibility, high sensitivity, multi-dimensional sensing, and high efficiency and portability, they are now widely used in many fields such as sports medicine, rehabilitation medical treatment, sports competition, military training, ergonomics, etc., which is conducive to accelerating medical rehabilitation, decreasing the load on the joints, increasing the ability of the human body to exercise, and avoiding sports injuries.

Wearable exoskeleton devices are typically worn on the joints to assist limb movements. The value of mechanical energy expenditure in the joints during daily activity should not be overlooked. Consequently, numerous studies explore the incorporation of EH systems into exoskeleton devices to accomplish multiple objectives, including EH and health monitoring. Hu et al.[155] developed a self-powered device integrated into an exoskeleton, utilizing a piezoelectric cantilever array driven by magnets (**Figure 11A**). This device efficiently captures mechanical energy during daily joint activities, taking advantage of the rising frequency phenomenon. It is capable of rapidly charging a 100 μF capacitor to 3 V in just 7 min. Additionally, it accurately measures the rotation angle of the patient's knee joint during knee joint rehabilitation exercises.

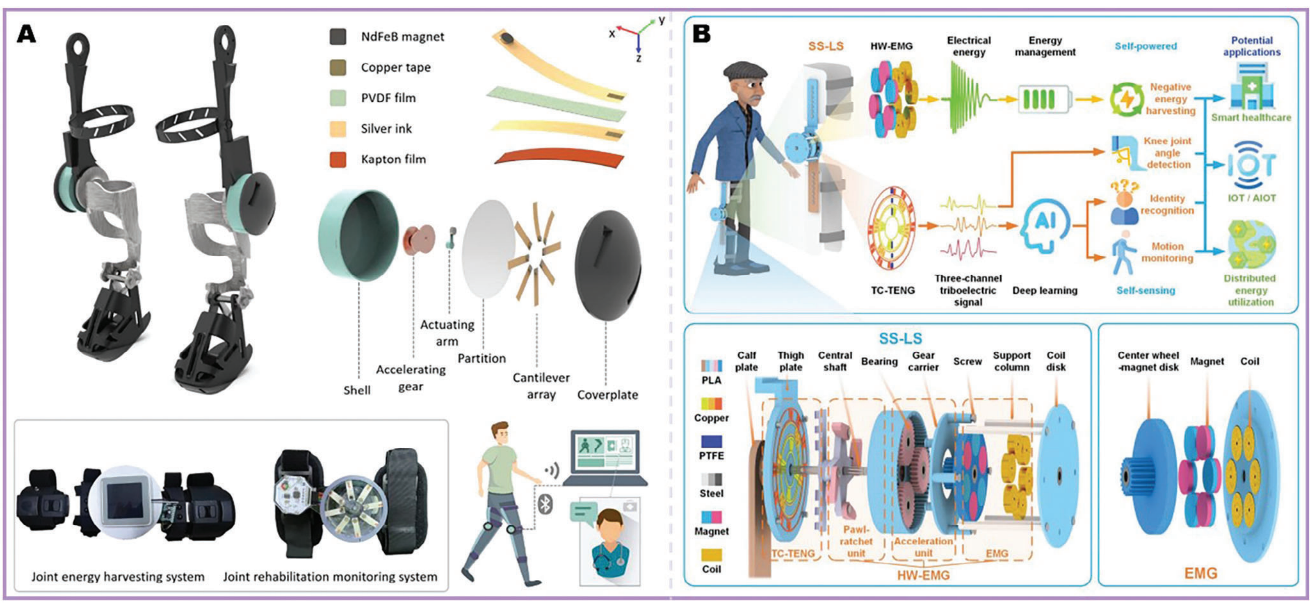

Figure 11. Wearable multifunctional devices based on the musculoskeletal system. A). Structure and application of the wearable exoskeleton based on the magnetic-driven piezoelectric cantilever generator. Reproduced with permission.[155] Copyright 2022, American Chemical Society. B). The self-powered and self-sensing lower-limb system (SS-LS) for smart healthcare. Reproduced with permission.[156] Copyright 2023, WILEY.

Kong et al.[156] introduced a self-powered sensing lower limb system that combines negative EH and motion capture features to enable intelligent healthcare (Figure 11B). The WMD enables the self-sustaining functioning of the system by utilizing a half-wave EMG, which efficiently captures the energy generated by human walking at a reduced energy collection expense. Furthermore, the implementation of the three-channel TENG based on binary coding allows the system to possess motion capture capability, correctly discerning the angle and direction of knee joint rotation. The bench test indicates that the EH module has an average output power of 11.2 mW, which is sufficient for powering Bluetooth modules or low-power sensors throughout multiple energy cycles. The three-channel voltage signal of TENG exhibits the properties of a binary signal, enabling precise detection of the angle and direction of rotation. Furthermore, with the long short-term memory (LSTM) deep learning model, the WMDs system achieves an impressive identity recognition accuracy of 99.68% and a motion state detection accuracy of 99.96%. In addition, the system demonstrated its capability in diagnosing Parkinson's disease, detecting falls, and monitoring three distinct training modes (sitting, balance, and walking training).

Aside from WMDs that rely on lower limbs, like the knee, there are also some self-energy support devices for elbows, shoulders, ankles, and so on (Figure 6).[131,157,158] In a word, research on musculoskeletal systems-based WMDs is in the midst of a boom, but there are still some difficulties that need to be broken through. Devices worn on joints, muscles, and other parts need to be further improved in terms of comfort and safety to prevent repeated movements from causing local tissue abrasion, wear, or interference with normal joint movement. The motion of musculoskeletal systems such as joints, is complex and changeable. The material selection and structure design of musculoskeletal system-based WMD devices should be personalized according to the physiological structure, range of motion, and force characteristics of different body parts.

4. Challenges and Prospects

In this review, we summarize the harvesting technologies and wearable forms of WMDs based on hEH, as well as the latest advances in related research. The combination of micro- or nanomaterials and novel structural design has led to a newer iteration of wearable electric devices toward malleability, softness, and miniaturization. Precise integration of the hEH, energy management system, flexible sensor, wireless transmission module, and other components enables multi-functional wearable devices to realize long-term working, multi-functional expansion, and multi-scenario applications. This series of newer breakthroughs make human society more convenient, intelligent, and sustainable. Despite the great achievements in this field, the future of WMDs still faces many tests and challenges (**Figure 12**):

1) At the material level, the development of breathable, durable, flexible, and stretchable materials remains an important element of multifunctional wearable electronic devices (e.g., e-textiles, e-skins, smart patches, etc.). In the future, these performances of materials will be continuously improved by using nanotechnology, engineering design, and structural optimization. The utilization of various materials (such as conductive materials, nanofibers, elastic polymers, etc.) to form composite structures (thin film structure, layered structure, 3D, controllable deformation structure, etc.) is expected to further optimize the flexible, stretchy, breathable, durable and other properties of WMDs, and promote the development of technology in this field. Considering the sustainability of materials, recyclable matrix materials are more in line with low-cost mass production and green environmental protection concepts. It is particularly important to explore the use of biocompatible materials to reduce potential allergic reactions and improve overall comfort for prolonged wear.
2) At the structural level, innovative designs of highly deformable, micro- and nano-structures will benefit performance and efficiency improvement. Besides to use experience and resources from other fields to enhance the value of research in this field. For example, inspiration from nature can provide ideas for the design of bionic structures. At present, the bio-inspired system has achieved some satisfactory results in the application of the human body, such as electronic skin, soft robot, intelligent contact lens, etc. There is no doubt that the innovation and breakthrough of the device structure is an important part of future research.
3) At the application level, wireless transmission, multi-functionalization, and high-level integration are the development trends of the IoTs era. Future WMD is no longer limited to a single application or scenario; multi-module composition and multi-dimensional application necessitate the support of materials, structure, processing, integration, and other disciplines. In addition, the general design principle should be followed, that is, the application of the device should be user-centric, not only technologically advanced, but also user-friendly.
4) On a technical level, as functional diversification advances, the power demand of WMD also rises, which puts forward higher requirements for power supply strategies based on hEH, circuit optimization management, and energy technology improvement. To achieve large-scale production of WMDs at an acceptable cost, it is necessary to formulate standardized production processes and quality inspection standards to achieve the consistency of different batches of products as far as possible, so as to provide possibilities for the implementation of commercialization and assembly line operations.
5) In terms of performance, there is still much room for improvement in WMD's anti-interference ability to withstand the environment (temperature, humidity, washing conditions, etc.), stability of long-term operation, timeliness and accuracy of closed-loop management and real-time feedback, and efficiency of energy conversion. Based on this problem, encapsulating materials and encapsulating technology are also worth exploring and improving.
6) We live in an information age where concerns about data security and user privacy are paramount. WMDs generate a large amount of data every moment, and how to collect, preprocess, store, manage, calculate, analyze, mine, model, and apply the mega-data poses new challenges to the key technologies of big data processing (such as cloud computing, AI algorithms, etc.). In the future, we should strengthen the exploration of security elements, privacy data processing

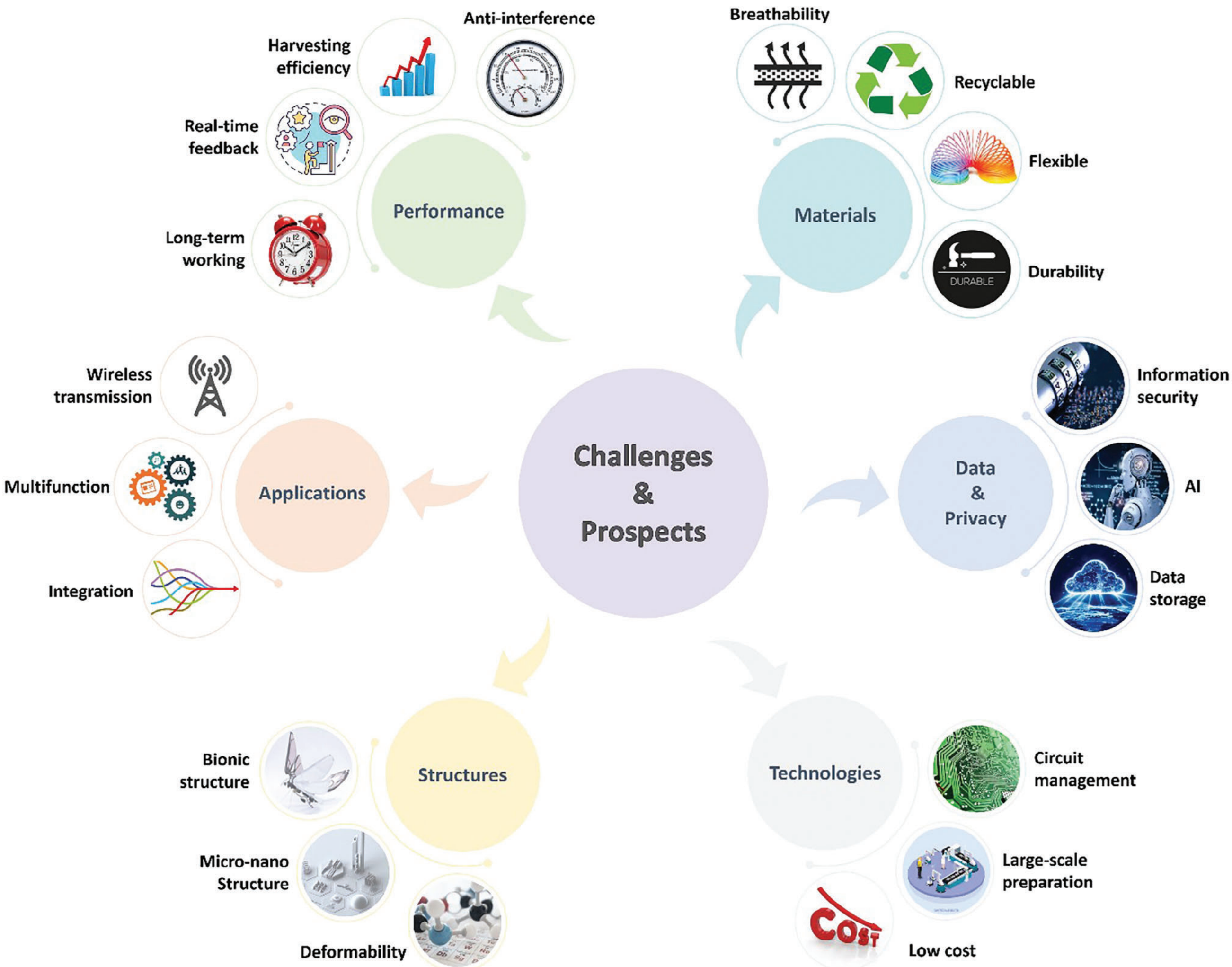

Figure 12. Future prospects of wearable multifunctional devices based on human-body energy harvesting.

technology, encryption technology, and other solutions to protect users' data security.

5. Conclusion

Wearable multifunctional electronic devices based on hEH provide users with new experiences that are convenient, comfortable, and environmentally friendly, and are becoming increasingly popular in healthcare, daily life, sports and athletics, and military scenarios. This paper reviews different hEH methods, their related principles, advantages and disadvantages, and research progress, as well as discusses in detail the wearable forms, materials, structures, and application demonstrations of WMDs based on human self-supplied energy. Finally, the current challenges and limitations in this research field are discussed, and the outlook is presented at the levels of materials, structures, applications, technological processes, performance, data, and user privacy. In conclusion, with the rapid development of materials engineering, flexible electronics technology, AI technology, and so on, passive, self-powered, green, miniaturized, lightweight, multifunctional, and highly integrated smart wearable devices are the way to go for future development.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

human-body energy harvesting, piezoelectric nanogenerator, self-powered, triboelectric nanogenerator, wearable devices

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Huaqing Chu received her Bachelor's degree from Shanxi Medical University in 2018. She is currently an M.D. student at the Department of Anesthesiology, National Cancer Center/Cancer Hospital, Chinese Academy of Medical Sciences, and Peking Union Medical College. Her research interests mainly focus on wearable electronics and drug-loaded microneedles.

Jiangtao Xue received his Bachelor's degree from Beijing Institute of Technology in 2016. He is currently a Ph.D. student at the School of Medical Technology, Beijing Institute of Technology. His research interests mainly focus on nanogenerators and wearable electronics.

Dan Luo received his B.Sc. and Ph.D. degrees at Peking University Health Science Center in 2008 and 2013, respectively. He worked at the Institute of Chemistry, Chinese Academy of Sciences in 2013, then transferred to China University of Petroleum-Beijing in 2015. Since 2021, he has joined the Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences as a professor. His research focuses on physiotherapy strategies based on self-powered devices.

Hui Zheng received his M.D. and Ph.D. from Beijing Tuberculosis Chest Tumor Institute in 2008, and a Bachelor's Degree from Harbin Medical University in 1992. He worked as a visiting scholar at Massachusetts General Hospital, Harvard Medical School in 2011. He currently is a professor, chief physician, and doctorial tutor at the Department of Anesthesiology, National Cancer Center/Cancer Hospital, Chinese Academy of Medical Sciences, and Peking Union Medical College. His research focuses on basic research of neurodevelopment and neurotoxicity and anesthesia-related clinical translational research.

Zhou Li received his Ph.D. from Peking University in the Department of Biomedical Engineering in 2010, and Bachelor's Degree from Wuhan University in 2004. He joined the School of Biological Science and Medical Engineering of Beihang University in 2010 as an associate professor. Currently, he is a professor at Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences. His research interests include nanogenerators, in vivo energy harvesters, self-powered medical devices, and biosensors.